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Monte-carlo Simulation of Light Propagation considering Characteristic of Near-infrared LED and Evaluation on Tissue Phantom

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Abstract

Currently, there are many techniques to measure subcutaneous fat of skin layers on clinical fields. Among many kinds of methods to measure subcutaneous fat, an optical method has especially many advantages. Moreover, it is appropriate to use during a surgery like liposuction. To implement the optical method, a simulation by LEDs is frequently performed. In the field of optics, there are several methods to simulate diffuse light, such as Monte-carlo simulation. Although the basic Monte-carlo simulation for light propagation is only based on using beam typed light source, we consider characteristics of a LED source and suggest a method to simulate the light propagation by the LED source.

To make the Monte-carlo simulation for a LED source, we modify the step of initializing photon in the simulation. First, we expand an initial area launching photons. Second, we apply stochastically the incident angle of photons. Third, we make the method performed differently according a contact area between LED source and turbid medium. Finally, we check the verification of our simulation compared with experimental results. The correlation coefficient between the simulation and the experimental results is 0.9771.

In this study, for developments of devices to measure the subcutaneous fat using a LED source, we make the valid method to simulate diffuse light. In the future, we will develop the equipment to measure a fat thickness and an irregularity of it during liposuction surgery, based on the simulation method we proposed.

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Keywords: Diffuse optics; Monte-carlo simulation; LED

1. Introduction

Currently, there are many techniques to measure subcutaneous fat of skin layers on clinical fields, such as magnetic resonance imaging (MRI), computer tomography (CT), ultrasound imaging (US) and dual-energy X-ray absorptiometry (DEXA) [1], [2]. They are widely used on clinical fields as a precise and accurate tool. However, these methods have many limitations such as a high cost and a risk of radiation. Likewise, it is not easy to use to measure subcutaneous fat during surgery needed to check the condition of the subcutaneous fat like liposuction surgery.

In contrast, methods on biomedical optics are more appropriate to measure the subcutaneous fat during surgery as an intraoperative tool. It is becoming widely researched and applied in a variety of research fields.

At 600-1300nm wavelength (called "Optical window"), light is absorbed small and penetrated well with dominant scattering on blood and water. Consequently, light propagation on tissue appears differently depending on optical properties of a tissue. Using the difference of diffuse light propagation on a tissue, we can estimate thickness of tissue on a multi-

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layered tissue such as skin layers [3].

To estimate the diffuse light on a tissue, it is necessary to know the optical properties of light source and tissue, and find the distribution of light on tissue. For a preliminary study, there are several methods to show the distribution of light on tissue are commonly performed; Radiative Transport Theory (RTE), Kubelka-Munk Model, Multi-flux Model, Adding-Double Method, Diffusion Approximation and Monte-carlo Method. Among these methods, Monte-carlo method and Diffusion Approximation are very widely used. However, Diffusion Approximation has not valid values on a narrow region around a light source. However, the Monte-carlo method to simulate the narrow region around a light source, have more valid results than the Diffusion Approximation. With this reason, it is being widely used on biomedical optics fields.

A Monte-carlo method is a statistical model introduced in order to find physical phenomena including biological tissues. In particular, the Monte-carlo method for the light propagation is that perform the launching, moving and termination of photons by the spread of a biological tissue using optical computer simulations [4]. But, in previous papers about the Monte-carlo simulation for the light propagation, Laser had been used as light sources on tissue. Furthermore, there had been already many researches about the Monte-carlo simulation for an application of a Laser source on biomedical optics fields [5], [6], but, not for a LED source.

In this paper, to know the optical effect and the property of a subcutaneous fat by a LED as the light source, we suggest the method of simulation to appropriate to estimate diffuse light on skin layers.

1.1. Objective

The Monte-carlo simulation has been performed commonly with a beam typed light source. There are rarely simulations considering the property of a LED. Moreover, the existing Monte-carlo simulation without considering the property of a LED source is used to validate an application of optical methods using LED sources [7]. In this paper, we deal with characteristics of a LED source as follows when contacting it on a tissue;

a. *It is not possible to assume LED as a light point source.*
b. *It has very wide radiation angles of light at an initial launching area.*
c. *Due to a round-shape of head, it is not entirely contacted with a tissue.*

Therefore, the objective of this paper is to suggest a method to make the Monte-carlo simulation considering characteristics of a LED source as above, as well as a validation of a proposed Monte-carlo simulation. A secondary objective is to find the property of optical tissue caused a radiation by a LED source.

1.2. Contents

The rest of this paper is organized as follows. Section 2 presents our Monte-carlo method for a LED source, including the method of initializing launch area, setting an incident angle, and considering refraction according contacted areas. Section 3 and 4 verify the simulation method through a comparison with the experimental data. Section 5 presents our conclusions. Finally, we describe the future work at Section 6.

2. Method

2.1. Overview

Monte-carlo simulation in this paper is based on the method proposed by S. A. Prahl al. [4]. The flowchart of their Monte-carlo method for light propagation is as figure 1. It consists of launching photons, generating a step-size of the photons, moving the photon with internal reflection, photon absorption and photon scattering. The details of Monte-carlo method of the light propagation in tissue has been described elsewhere [4], [8], so we only explain the photon initializing of the Monte-carlo method, because there are only difference in the part, the launching photons with another about the source.

An overview of the proposed photon launch in this paper is as figure 2. It consist of 3 parts.

In this research, the considerations as below.

a. *Initial launch area (2.2)*

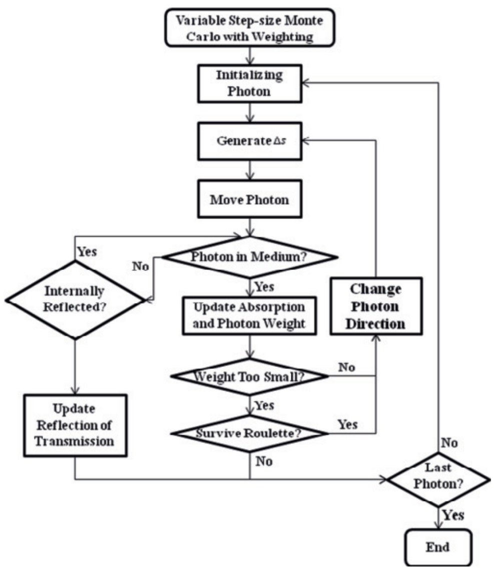


Fig. 1. A flowchart of Monte-carlo simulation by S. A. Prahl. Al.

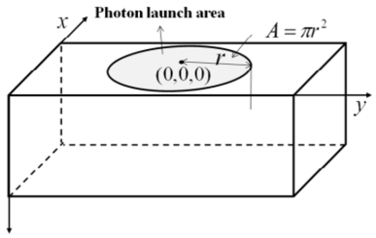


Fig. 2. A schematic of an initial launch area.

b. Radiation angle (2.3)
c. Refraction according contacted area(2.4)

Each consideration needs to have 3 assumptions for an application of the Monte-carlo method for LED source. It is as below;

Assumptions:

a. All photons are uniformly generated from areas of the cross section of a LED source. For (2.2)
b. All photons have same probability density function with a distribution of a radiation angle on the LED specification. For (2.3)
c. A photon launch area can be assumed as a flat area by Assumption a. and b. For(2.4)

2.2. Initial launch area

LED is not a point source, but a very small array of them. So, a LED source has to be assumed as a set of point sources. To apply this on our Monte-carlo simulation, we get the radius of the LED, r and generate the position launching a photon, x_0 and y_0 with the uniform probability distribution. The probability density function for generating the launch point in this paper is,

$$f_n(x_0,y_0)=\begin{cases}\dfrac{1}{\pi r^2} & for r \geq \sqrt{x_0{}^2+y_0{}^2}\\ 0 & for r \leq \sqrt{x_0{}^2+y_0{}^2}\end{cases} \qquad (1)$$

In this equation, x_0 and y_0 are the launch position of n-photon. We set the center of a LED as (0, 0, 0) and the coordinates axis as figure 2. It shows the schematic of accumulated initial points of a LED source. That is, photons are generated uniformly on the area of LED.

2.3. Incident angle

A radiation angle of a LED source is very wide. To get meaningful diffuse light by a LED source, it has to be considered the radiation angle of photons from the specification of the LED. Therefore, the radiation angle of the LED source is applied as an incident angle at the part of the launching photons.

The radiation angle of the LED (Shuen 1W series, Everlight Electronics Co., Taiwan) on a relative intensity is as figure 3. This distribution is symmetric, bell shaped and single-peaked. So it can be approximated assumed as Gaussian probability distribution.

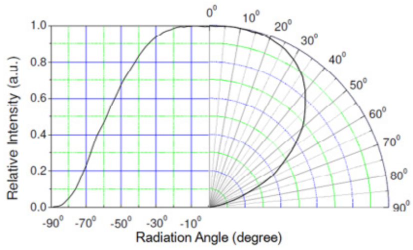


Fig.3. A relative intensity of LED on the radiation angle.

Using the Gaussian probability distribution, a random number generator is configured with the mean and the standard deviation of the radiation angle. Because the intensity of light is the number of photons per time on quantum mechanics, the intensity of light on radiation angle is assumed as the probability of the radiated photon.

The Gaussian random number generator generates angles for the incident angle of n-photons with a given stochastic frequency. The angles from the number generator are used as the elevation angle, θ at the spherical coordinates $(1,\theta,\varphi)$. In case of the azimuth angle, φ, because it is not related with the incident angle, we generate the number of the azimuth angle by a uniform random generator. The probability density functions for generation of the elevation and the azimuth angle are respectively as follows:

$$f_\theta(\theta)=\frac{1}{\partial\sqrt{2\pi}}e^{-\frac{1}{2}(\frac{\theta-\mu}{\partial})} \quad for -90<\theta<90 \qquad (2)$$

$$f_\varphi(\varphi)=\frac{1}{2\pi r^2} \quad for -180 \leq \varphi \leq 180 \qquad (3)$$

To calculate the first incident direction, (μ_x,μ_y,μ_z) from spherical coordinates by each random number generator, we can calculate as follows:

$$\text{incident angle} = (1,\theta,\varphi) \qquad (4)$$

Here, θ and φ are the generated angles at spherical coordinates by the Gaussian random number generator.

The Cartesian coordinates is retrieved from the spherical coordinates by,

$$\begin{aligned} \mathrm{x} &= \sin\theta\cos\varphi \\ \mathrm{y} &= \sin\theta\sin\varphi \\ \mathrm{z} &= \cos\theta \end{aligned} \qquad (5)$$

When θ_x and θ_y are the elevation angles with x- and y-axis, they are calculated as follow:

$$\theta_x = \frac{x}{\sqrt{x^2+z^2}} = \frac{\sin\theta\cos\varphi}{\sqrt{\sin^2\theta\cos^2\varphi+\cos^2\theta}}$$
$$\theta_y = \frac{y}{\sqrt{y^2+z^2}} = \frac{\sin\theta\sin\varphi}{\sqrt{\sin^2\theta\sin^2\varphi+\cos^2\theta}} \tag{6}$$

The incident direction (μ_x, μ_y, μ_z) can be calculated as follows:

$$\mu_x = \sin\theta_x$$
$$\mu_y = \sin\theta_y \tag{7}$$
$$\mu_z = \cos\theta$$

Eventually, it calculates new position, (x_1, y_1, z_1) using the incident direction (μ_x, μ_y, μ_z).

$$\mathrm{x}_1 = \mathrm{x}_0 + \mu_x \Delta \mathrm{s}_\mathrm{x}$$
$$\mathrm{y}_1 = \mathrm{y}_0 + \mu_y \Delta \mathrm{s}_\mathrm{y} \tag{8}$$
$$\mathrm{z}_1 = \mathrm{z}_0 + \mu_z \Delta \mathrm{s}_\mathrm{z}$$

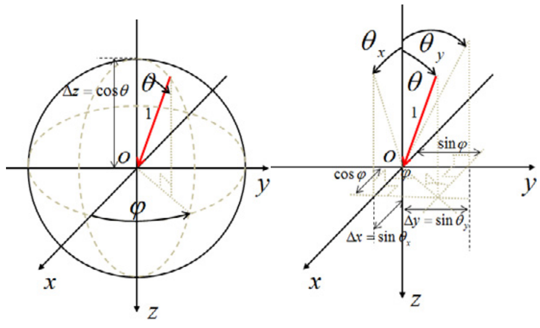
The initial launch point is (x_0, y_0, z_0). θ and φ are the elevation and the azimuth angle at the spherical coordinates. θ_x and θ_y are projected angles in xz - and yz -plane respectively at the Cartesian coordinates. They are shown in figure 4. Here, the first step size $(\Delta\mathrm{s_x}, \Delta\mathrm{s_y}, \Delta\mathrm{s_z})$ is calculated with the absorption coefficient, μ_a and the reduced scatter coefficient $\mu_s{'}$ based on similarity relation theory as follows:

$$\Delta\mathrm{s_x} = \frac{\cos\varphi}{\mu_a + \mu_s{'}}$$
$$\Delta\mathrm{s_y} = \frac{\sin\varphi}{\mu_a + \mu_s{'}} \tag{9}$$
$$\Delta\mathrm{s_z} = \frac{1}{\mu_a + \mu_s{'}}$$

2.4. Refraction according contact area

When the photon is radiated from the sources, it is occurred a non-contact area on turbid medium, caused by a head of the round-shape on LED source. It is the reason of difference of the refractive effect according the photon launch position of a LED source. The contact area and non-contact are shown in figure 5(a). This is one of unique characteristics of LED source different from a Laser source.

For ease to calculate, it is approximated as figure 5(b). Here, the errors of distance occur at the non-contact area.



(a) (b)

Fig.4. An incident angle (a) the spherical coordinates (b) the Cartesian coordinates

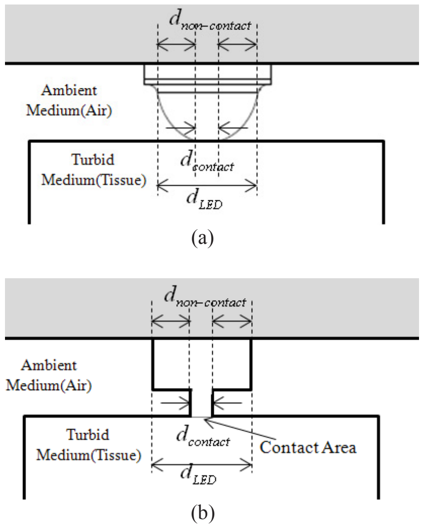


Fig. 5. Contacted area between LED and tissue.
(a) An appearance of LED contacted on tissue.
(b) Simple model for LED contacted on tissue

However, it is only a few micro meter, since that, it is ingnored in this paper.

When the photons are radiated from the non-contacted area, it is passed to the turbid medium (tissue) through the ambient medium (air). It means that refractive effects between the turbid and the ambient medium have to be considered in case of the non-contact area. A schematic of the refraction effects depending on the state of a contact is shown in figure 6. In case 1 in figure 6, because LED source is contacted with the turbid medium, it is not considered about the effects of refraction. Eventually, the incident direction is same as one at Section 2.2. In contrary, the case 2 gets the effects of refraction between the ambient medium and the turbid medium. In case of this, the incident direction (μ_x, μ_y, μ_z) by a refraction angle, α , can be expressed as (10).

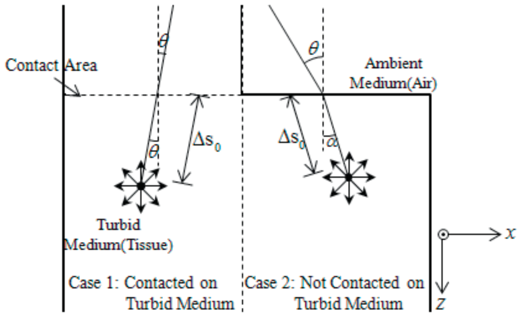


Fig. 6. Contacted area between the LED source and the turbid medium. (a) An appearance of LED contacted on tissue. (b) Simple model for LED contacted on tissue.

$$\mu_y = \sin\alpha_x = \frac{n_0}{n}\sin\theta_x$$
$$\mu_y = \sin\alpha_y = \frac{n_0}{n}\sin\theta_y \qquad (10)$$
$$\mu_z = \cos\alpha = \frac{n_0}{n}\cos\theta$$

Also, in the non-contact case, the photon energy is attenuated due to specular reflectance. To quantify it, we use a coefficient of the amplitude reflection coefficients for s- polarized light R_s and for p-polarized light R_p at Fresnel's equation. Using R_s and R_p, an attenuation by the refraction is calculated as (10). Consequently, the weight is 1 in case 1, because of no refraction. In the case 2, the weight is attenuated as below;

$$\textit{case 1}: \quad w = 1$$
$$\textit{case2}: \quad w = 1 - \frac{R_s + R_p}{2} \qquad (11)$$

Here, $R_p = \dfrac{n_0\cos\theta - n\cos\alpha}{n_0\cos\theta + n\cos\alpha}$, $R_s = \dfrac{n_0\cos\alpha - n\cos\theta}{n_0\cos\alpha + n\cos\theta}$

3. Experiments

3.1. Experiments preparation

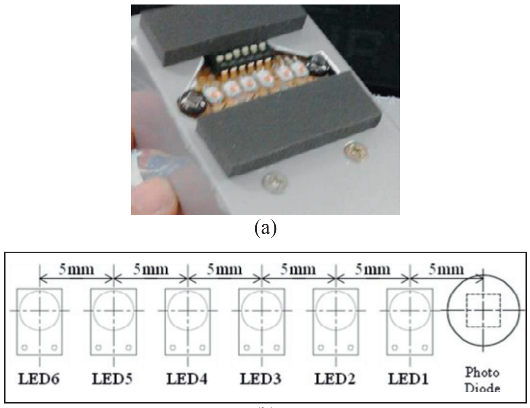
Measurement device: To verify the Monte-carlo simulation for a LED source, we develop a measuring device as figure 7(a). In this device, 6 near-infrared LED (730nm) and 1 photo-diode are equipped. These are arranged as figure 7(b). The each interval of each component is 5mm. The specifications of them are respectively as Table 1 and Table 2.

Table 1. LED specification

Type	Size (Sensor only)	Dominant Wavelength	Radiation Angle
SMD	ϕ 1.2mm	730nm	-60°~+60°

Table 2. Photo-diode specification

Size (Sensor only)	Dominant Wavelength	Viewing Angle
3.0mmx3.0mm	30nm	-60°~+60°



(a)

(b)

Fig. 7. An appearance of a measurement device with 6 LED and 1 photo-diode (a) An appearance of a measurement device (b) An arrangement of 6 LED and 1 photo-diode

Liquid Phantom: To make a liquid phantom having an optical property of tissue, especially subcutaneous fat. We use the Intralipid 10% (Lipision, JW Pharm., Korea) as a scattering material and india ink (Rotring, Germany) as an absorption material. For the experiment, the liquid phantom is made to have the specific optical property at 730nm as Table 3. A recipe is referred another papers about making liquid phantoms [9], [10], [11].

Table 3. An optical property of liquid phantom at 730nm for simulation

Refractive Index, n	Absorption Coefficient μ_a (cm^{-1})	Reduced Scatter Coefficient $\mu_s{'}$ (cm^{-1})
1.4	0.1	11

3.1. Experiments

To verify the Monte-carlo simulation for a LED source, an experiment is performed on the phantom using the device. The intensity of light distributed on the phantom is measured using the device.

4. Result & Discussion

For the verification of the Monte-carlo simulation for a LED source, we compared between the simulation data and the measured data. Firstly, we get the result from our Monte-carlo simulation as figure 8. For the simulation, the photon number is set as 1,310,720 and the optical property in Table 3 is inserted to the model. The measured data are divided by the value at 5mm. It is for removing properties of optical intensity of components and using the slope value. At that time, we set the width of the contact area as the entire width of the LED, 2.0mm. To make each scale same, we normalize both data 0 to 1 at distance 5mm to 30mm. And then, both results are calculated the 2nd regression. They are shown in figure 9. The correlation coefficient between them is calculated as 0.9771. From this result, we can estimate that it validate that the Monte-carlo simulation for a LED source is available to estimate diffuse photon propagation.

5. Conclusion

In this research, we suggest the method to simulate the diffuse light from a LED source based on Monte-carlo simulation. For this simulation, we consider the characteristic of LED. First, we expand the photon launch area. Second, the incident angle is stochastically applied based on a LED specification. Third, we make the simple model of LED and apply the refractive effects on the simulation. In addition, we verify an effectiveness of the simulation. In this paper, we prepare the method to estimate diffusion reflection of a LED source on the tissue.

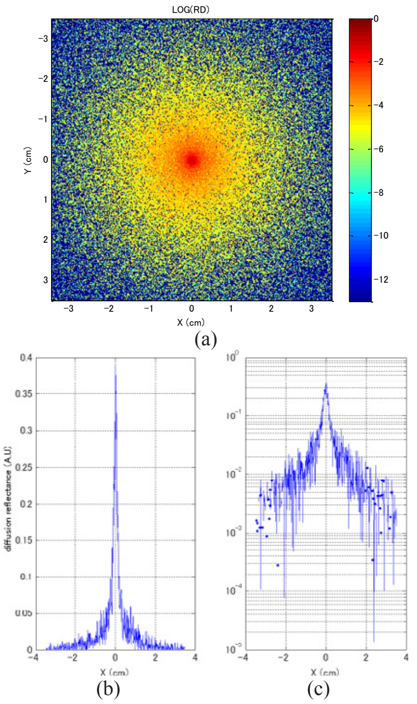


Fig. 8 Results of the Monte-Carlo simulation for a LED source. (a) Diffusion reflection (xy-plane) (b) Cross-section of x-axis (c) Cross-section of x-axis (log scale)

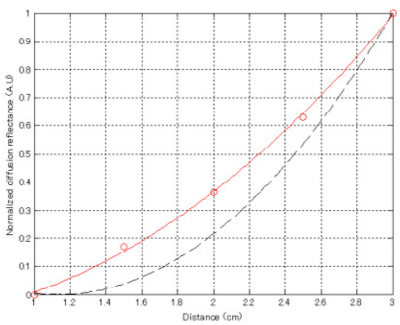


Fig. 9. Comparision of the normalized results at 730nm (red line: measured data, black line: simulation data)

6. Future Work

We should evaluate the simulation result under each difference of contact area with turbid medium. From the measured data on the difference of a contact area with turbid medium, we will evaluate the Monte-carlo simulation for LED source more. In further, we implement an intraoperative diagnosis device for Liposuction using this simulation results.

Acknowledgements

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